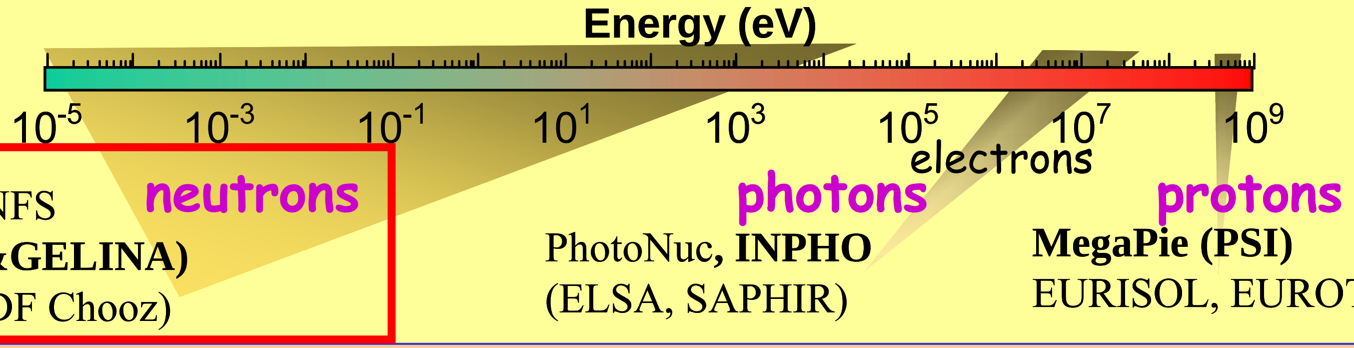
Modeling & Nuclear Measurements (MNM)



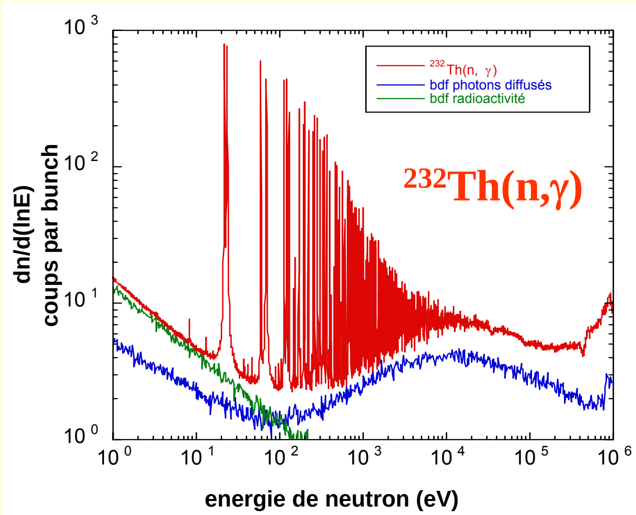
MiniInca (ILL), NFS
n_TOF (CERN&GELINA)
DoubleChooz (EDF Chooz)

PhotoNuc, **INPHO**
(ELSA, SAPHIR)

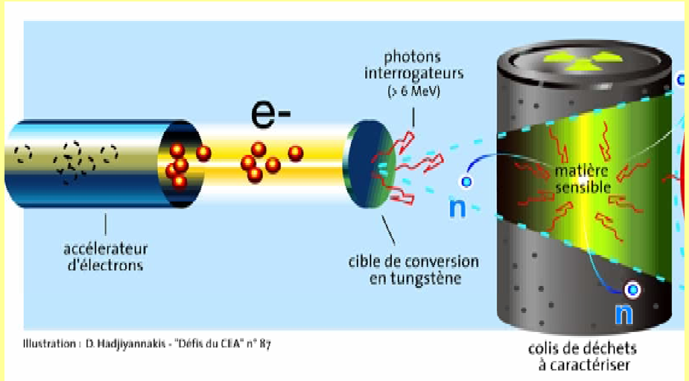
MegaPie (PSI)
EURISOL, EUROTRANS (EU)

Basic Nuclear Data Measurements, Modeling and Instrumentation for:

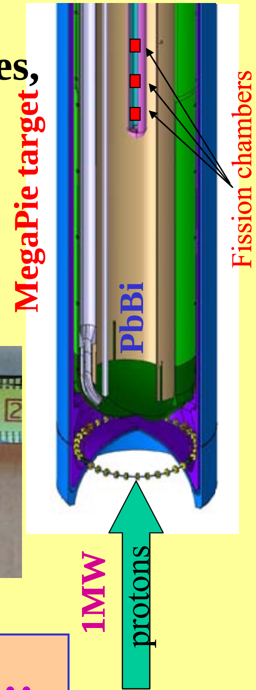
Innovative fuel cycles & transmutation of nuclear waste



Characterization of waste containers & trafficking of nuclear materials



Spallation neutron sources, RIB facilities & ADS



In collaboration with DEN, DRT, DAM, CNRS/IN2P3, NEA/OECD, …

Contact: ridikas@cea.fr, CEA Saclay

Neutrons For Science (NFS) @ SPIRAL-2

Danas Ridikas for NFS collaboration

CEA Saclay, DSM/IRFU/SPhN, 91191 Gif-sur-Yvette, France

Neutrons For Science (NFS) at SPIRAL-2

X. Ledoux[1)], M. Aïche[2)], G. Ban[3)], G. Barreau[2)], P. Baumann[4)], P. Bem[5)], E. Berthoumieux[6], V. Blideanu[6)], J. Blomgren[7)], S. Czajkowski[2)], P. Dessagne[4)], D. Doré [6)], E. Dupont[6)], T. Ethvignot[1)], U. Fischer[8)], F. Gunsing[6)], B. Jacquot[9)], B. Jurado[2)] , M. Kerveno[4)], F. R. Lecolley[3)], J. L. Lecouey[4)], F. Negoita[10)], S. Oberstedt[11)], M. Petrascu[10)], A.J.M. Plompen[11)], F. Rejmund[9)], D. Ridikas[6)], G. Rudolf [4)], O. Shcherbakov[12)], G. Smith[13)], S.P. Simakov [8)] , J. Taïeb[1)], I. Tsekhanovich[13)]

1) CEA/DIF, DAM/DPTA, 91980 Bruyères-le-Châtel Cedex, France

2) CEN Bordeaux-Gradignan, 33175 Gradignan, France

3) LPC, ISMRa et Université de Caen, CNRS/IN2P3,France

4) IPHC, Strasbourg, France

5) Nuclear Physics Institute, 25068 Řež, Czech Republic

6) CEA Saclay, DSM/IRFU, Gif-sur-Yvette, France

7) Department of Neutron Research, Uppsala University, Uppsala, Sweden

8) FZK, Karlsruhe, Germany

9) GANIL, CEA/CNRS, Caen, France

10) NIPNE, Bucharest, Romania

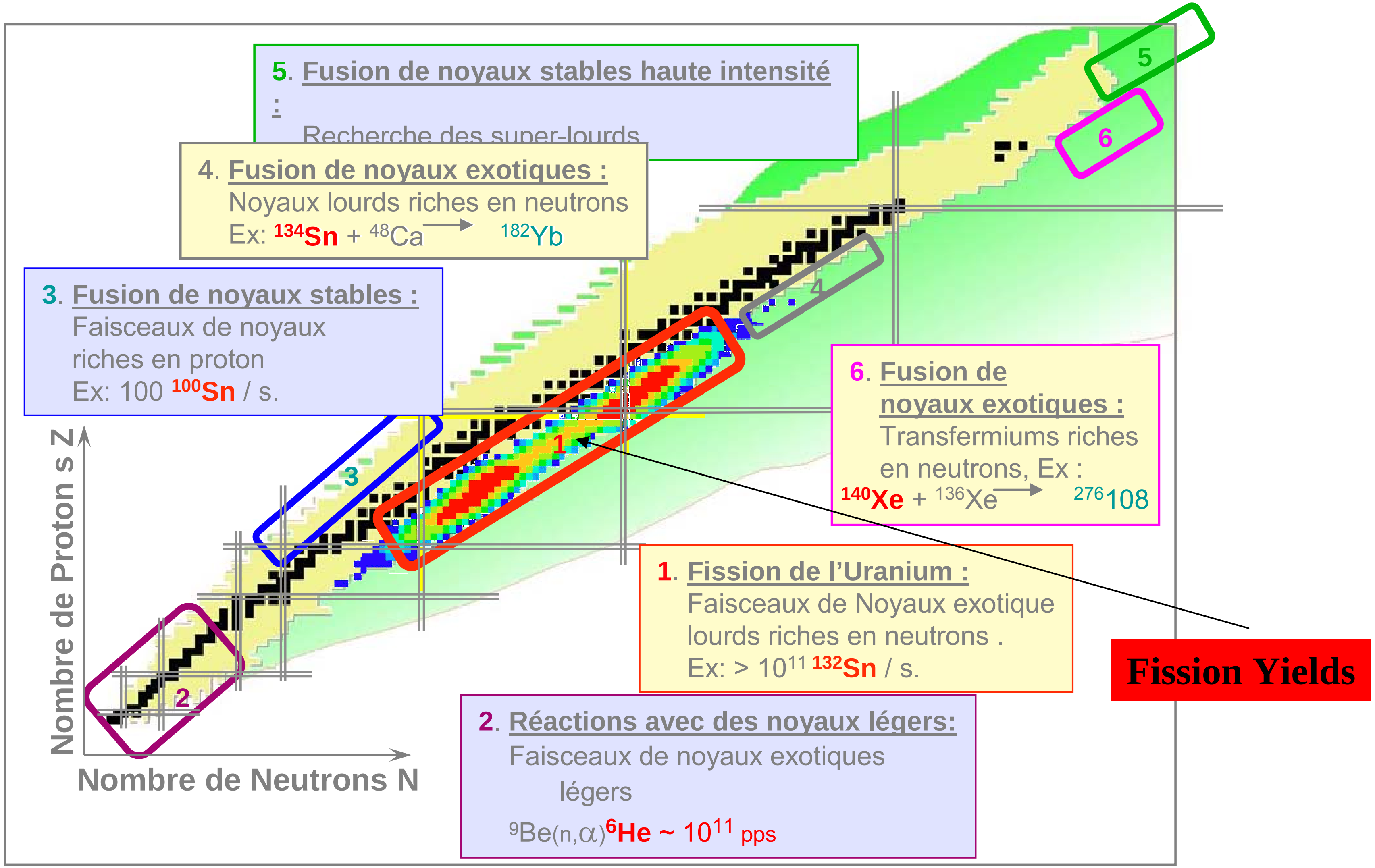
11) IRMM, Geel, Belgium

12) PNPI, Gatchina, Russia

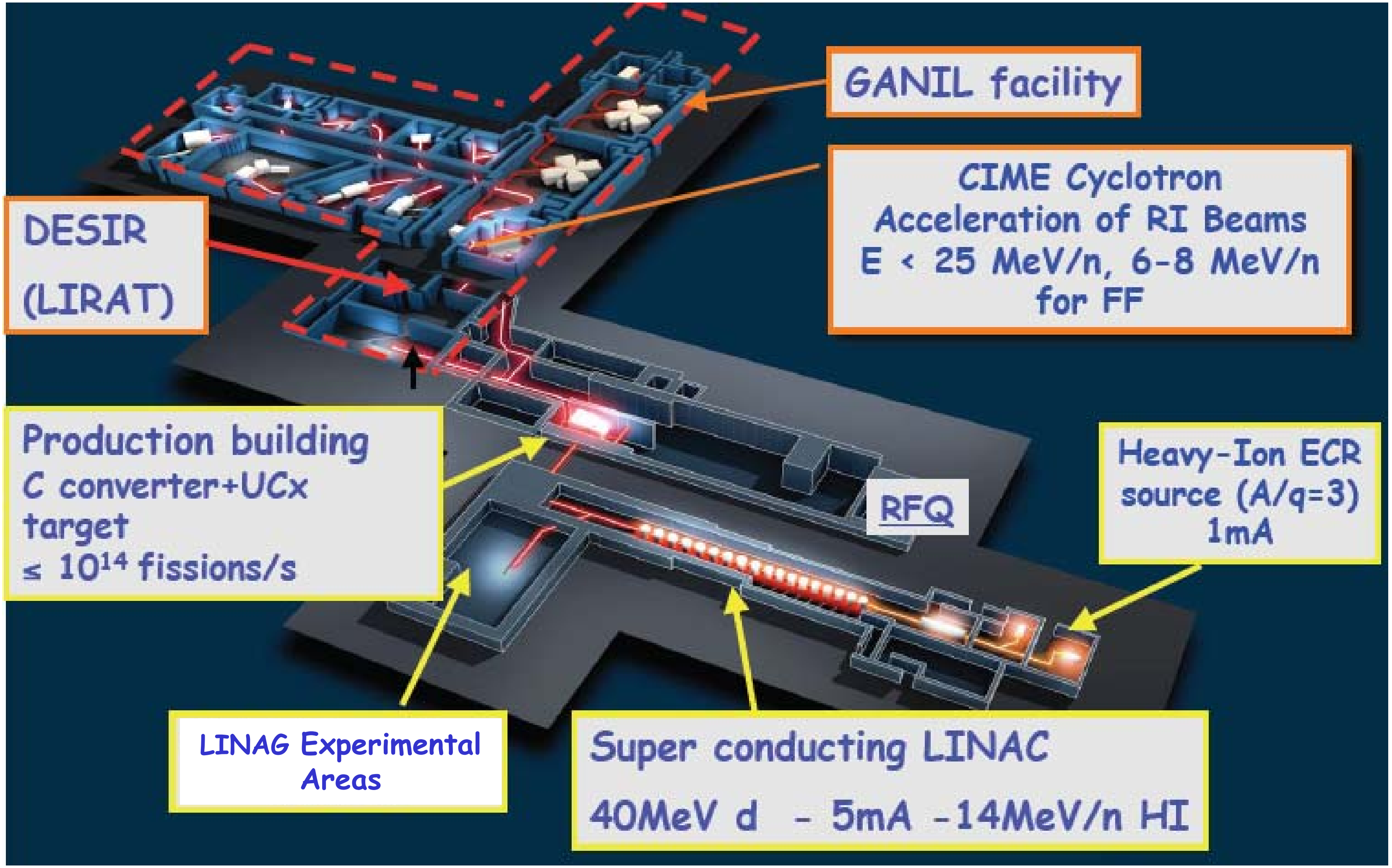
13) University of Manchester, Manchester, UK

…

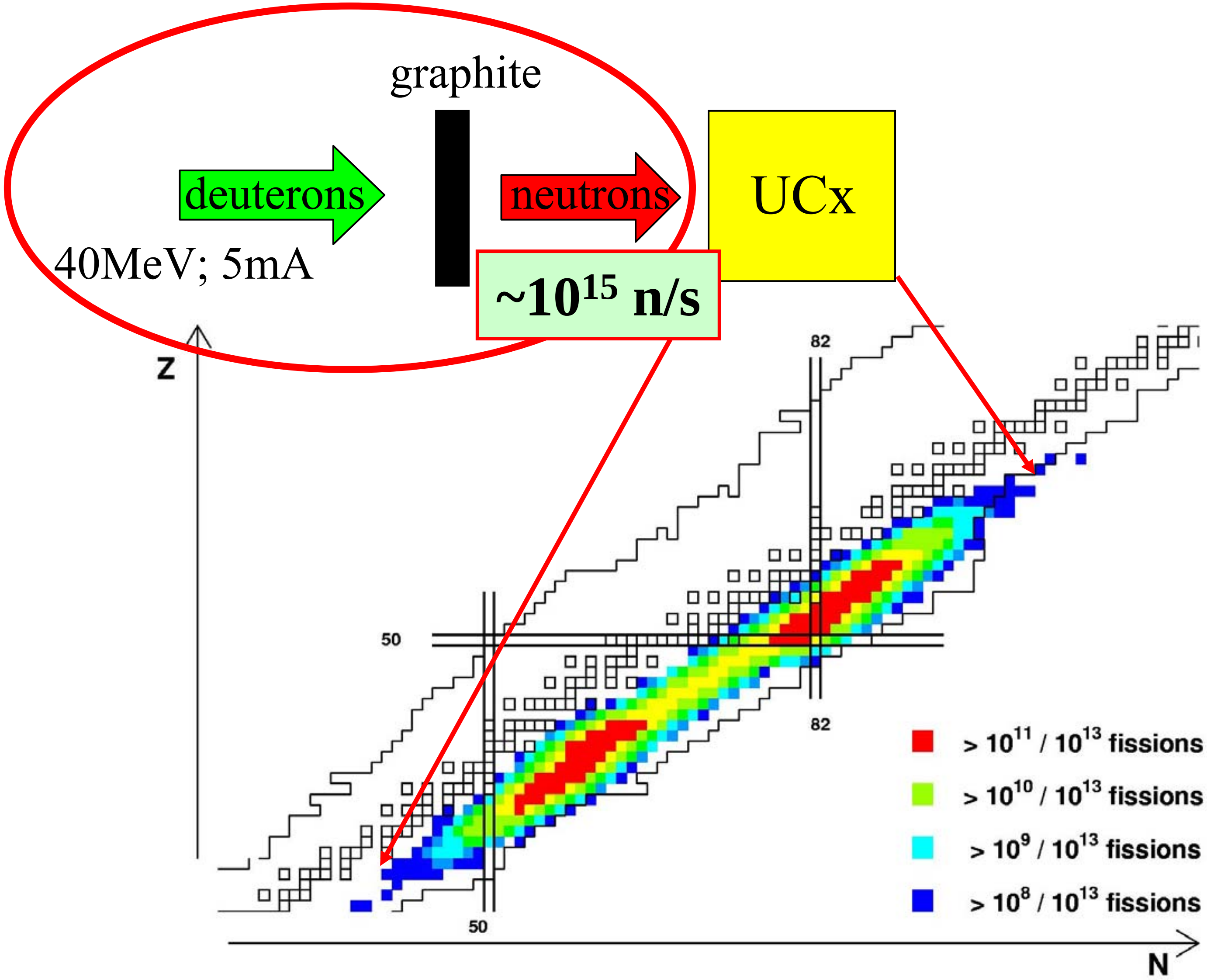
Physics with SPIRAL-2



Layout of SPIRAL-2



~2012(?) ~2014(?)


graphite
deuterons
neutrons
UCx
40MeV; 5mA
~10^15 n/s
Z
N
82
50
50
82
> 10^11 / 10^13 fissions
> 10^10 / 10^13 fissions
> 10^9 / 10^13 fissions
> 10^8 / 10^13 fissions

Important Events

2004 International Workshop on Neutrons for Science (NFS) at SPIRAL-2, GANIL, Caen, France; 13-14 December 2004; organized by D. Ridikas (CEA) and M. Heil (FZK)

2005 D. Ridikas et. al, "Neutrons for Science (NfS) at SPIRAL-2: Physics case", Internal report DAPNIA 05-30,CEA Saclay, France (2005)

2006 A. Plompen, "ND Needs for Nuclear Energy (fission) and Possible Contributions of SPIRAL2"
U. Fischer, "ND needs for Fusion technology and possible contribution by SPIRAL2"
15th Colloque GANIL, Giens, France (2006)

2006 LoI for SPIRAL-2, coordinators X. Ledoux (CEA) and S. Simakov (FZK)

2007 NFS – FP7 project within "Preparatory Phase for SPIRAL-2"; coordination by X. Ledoux (CEA)
- Physics Experiments
- Neutron production targets
- Beam collimation system
- Beam monitoring system
- Data acquisition system

Contact: ridikas@cea.fr, CEA Saclay

NFS

Use of the beams delivered by the LINAG to create a neutron facility with two components :

Pulsed Neutron beam

Irradiation station

Characteristics of the LINAG primary beams:

- deuteron 40 MeV
- proton 33 MeV
- I_{max} = 5 mA
- Pulsed beam F_0 = 88 MHz T=11 ns
- Burst width = 200 ps

General Physics Case

Reactions with fast neutron induced reactions are of first importance in the following topics :

- New generation (Gen. IV) fast reactors
- Fusion technology, test bench for IFMIF
- Studies related to hybrid reactors (ADS)
- Validation of codes and data libraries
- Nuclear medicine
- Development and characterization of new detectors
- Irradiation of chips and electronics structures used in space
- Production of radioactive targets
- …

Neutron spectra accessible at NFS

<u>Continuous spectrum :</u>

C(d,n) or Be(d,n)

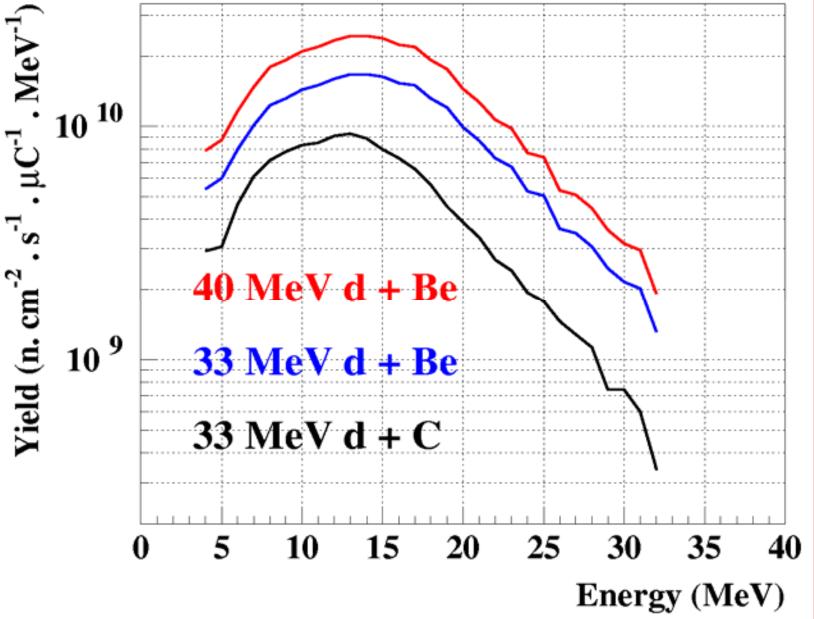
E_{max} = 40 MeV

<E> = 14 MeV

thick converter (1cm)

Meulders et al., Phys. Med. Biol. (1975)vol 20 n°2, p235

→Similar to IFMIF spectrum



<u>Quasi-monoenergetic beam :</u>

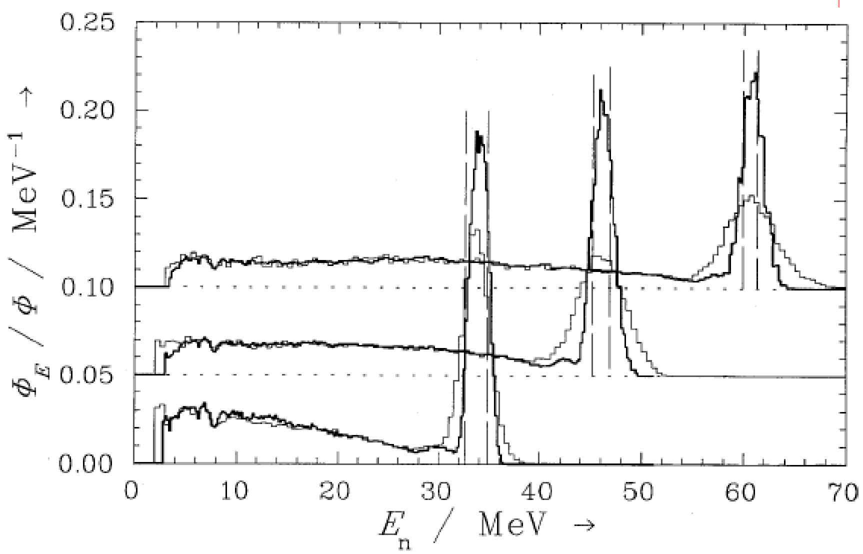
^{7}Li(p,n)^{7}Be   Q=-1.64 MeV

Thin converter (1-3 mm)

E_p = 3 – 33 MeV

$E_n \approx E_p$ –2 MeV

Schumacher et al.,NIMA421 (1999) p2843



NFS Facility

Converter cave

- clearing magnet
- beam dump
- Irradiation stations

  neutron, proton and deuteron

  activation measurement

Experimental Hall

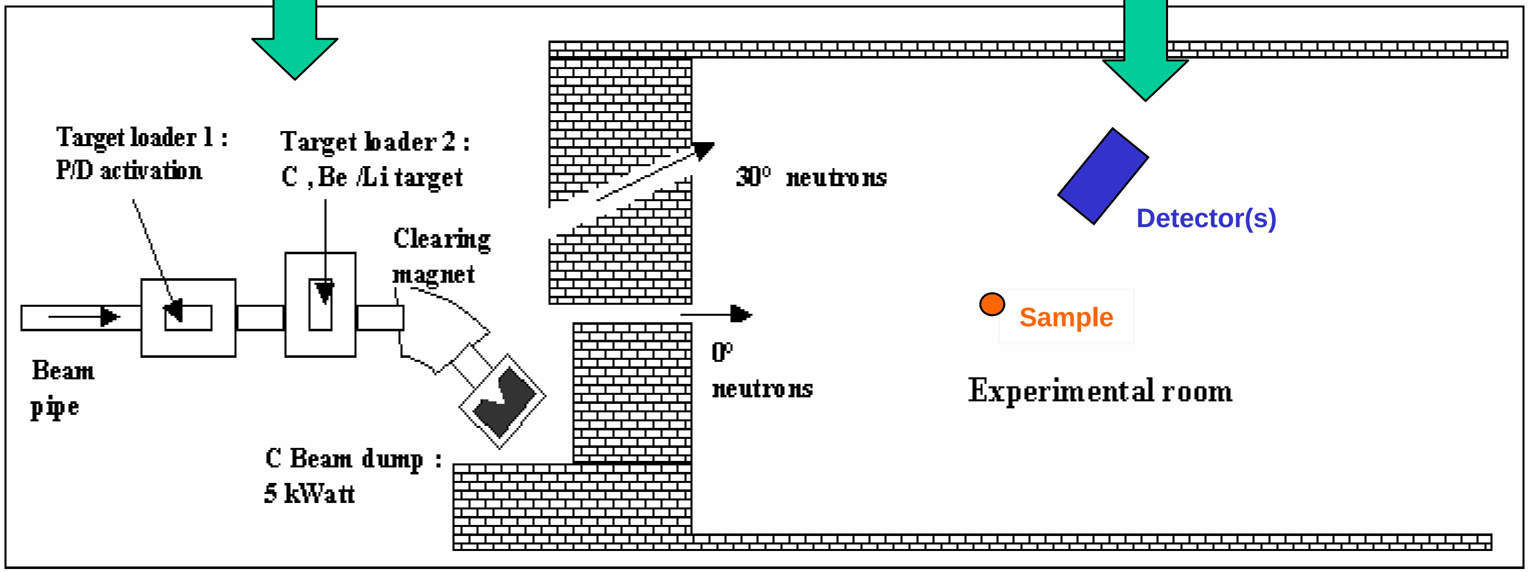
- beam lines

  0° high energy

  30° (optional)
- size (L□l) ≃ (30m □ 6m)

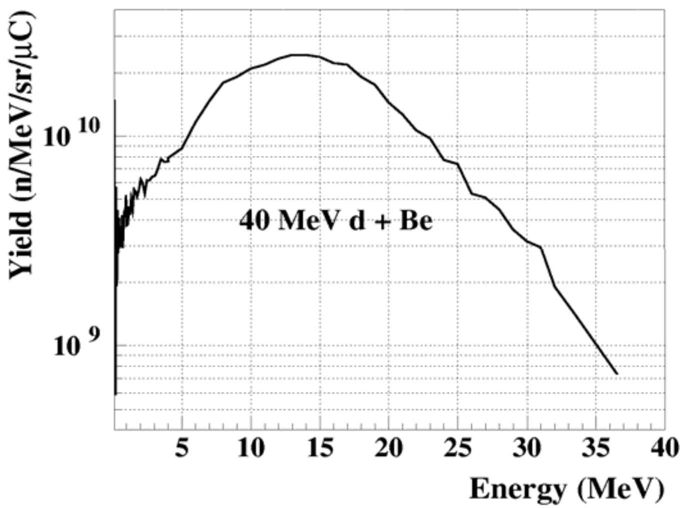
  time-of-flight measurement

  experimental set-up position

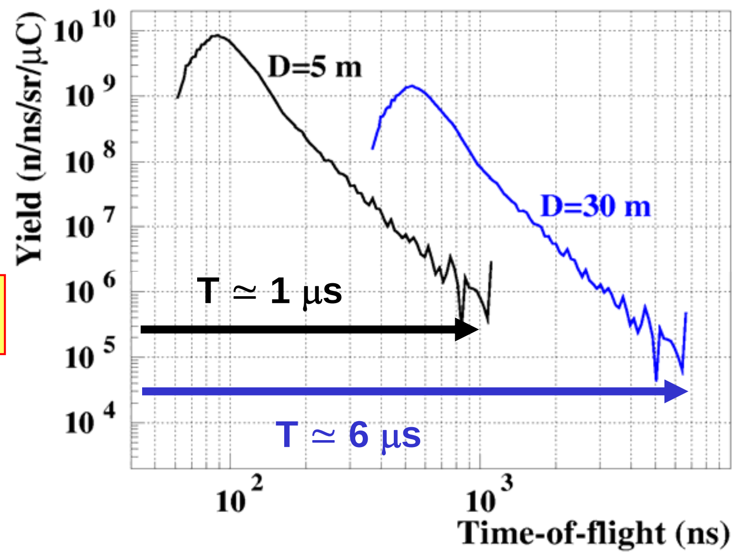


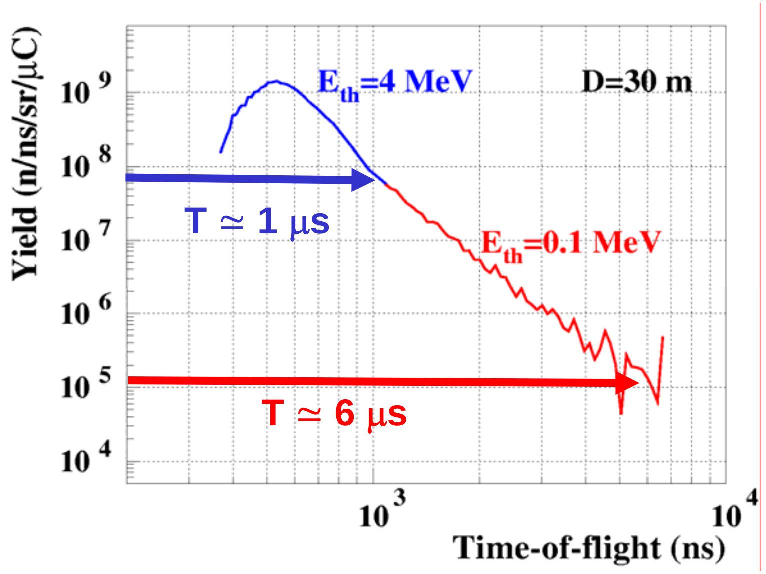
Beam repetition rate

Requirement: differentiation of 2 neutrons with the ToF **t** and **t+T**



T_{LINAG} = 11 ns



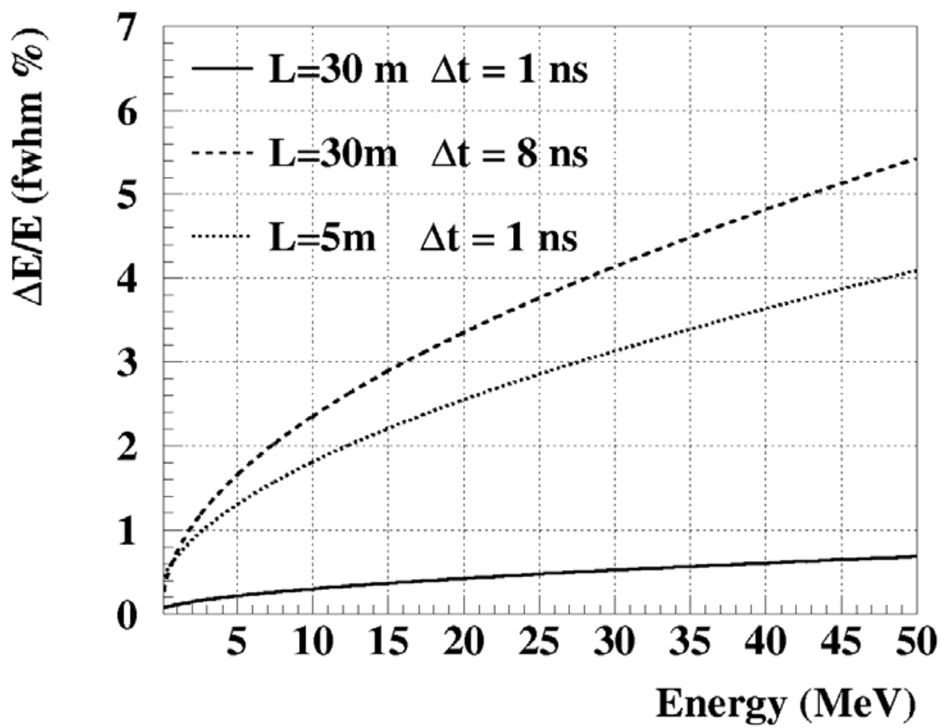


The beam must be divided by a factor N :
- **a burst selector : one burst over N**
- **$I = I_{max} / N$, with I_{max}=5mA**

L(m)	E_{th} (MeV)	T(µs)	N	I_{max}(µA)
5	0.1	1	100	50
30	0.1	6	600	8
30	4	1	100	50

Energy resolution

The neutron energy is measured by time-of-flight technique



$$\frac{\Delta E}{E} = \gamma(\gamma+1)\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

Δt : Full time resolution :

Beam $\simeq$ 1 ns

Detector

$\Delta t \simeq$ 1 ns scintillator

$\Delta t \simeq$ 8 ns HPGe

Fast detector : high resolution measurement

Slow detector : ΔE/E < 5% for L=30 m

Good resolution measurements require :

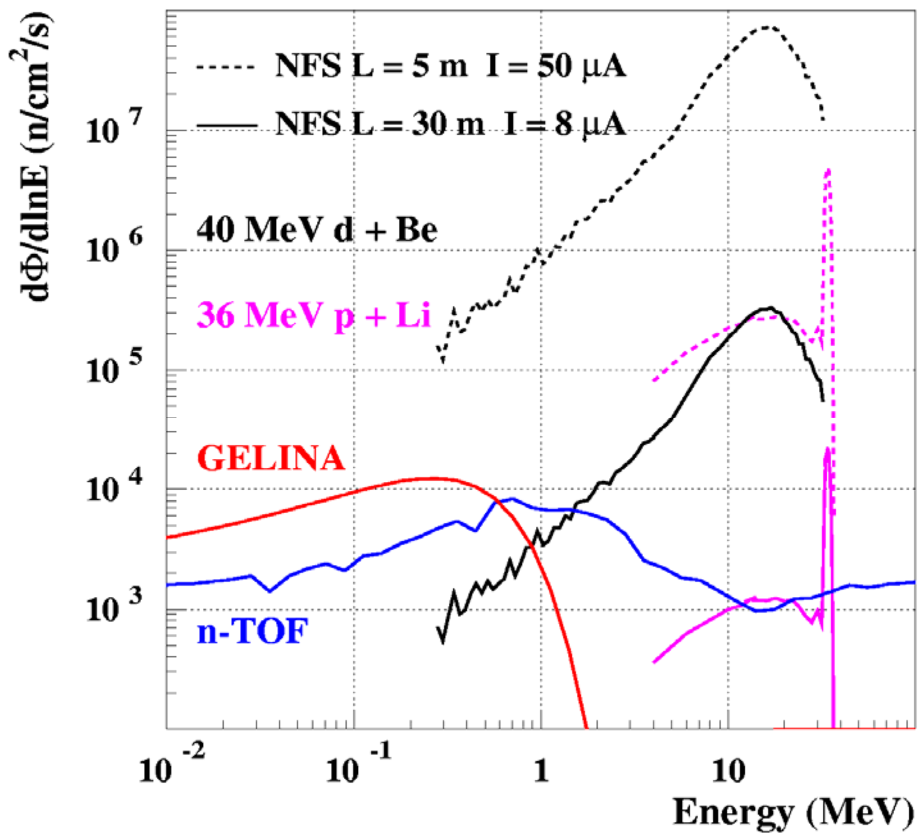
- A unique burst selector
- Burst duration on converter < 1ns (buncher might be needed)

Comparison with other neutron beam facilities

Spiral-2 :
.... high intensity
——— high resolution

n_TOF : CERN,
spallation, L=185 m, F=0.4Hz

GELINA : Geel,
Photonuclear, L=30m, F=800Hz



- E_n: from 0.1 MeV to 40 MeV
- High flux { small samples, shorter experiments / coincident experiments
- Reduced γ flash

→ Complementary to the existing facilities

→ 0.1-40 MeV energy region: fission + fusion

Reactions and processes of interest

Fission

- Need of data for fast neutron for minor actinides
- Cross-sections
- Neutron, gamma multiplicity and spectra
- Fragment yields
- Delayed neutrons
- Fundamental physics

Neutron multiplication

- (n,xn) reactions
- main isotopes

Scattering

- Secondary neutron energy and angle
- Differential cross section, main isotopes
- Inelastic scattering, main isotopes

Charged particle production

- gas production H,He
- Radiation damage
- Secondary reactions
- Composite particles →no model works

Motivation: physics with nToF

(n,n') and (n,xn) reactions at energies from 0.1 to 35 MeV

a) ADS, GenIV reactors, fusion devices, security installations, ...

b) radiation shielding, damage rates, nuclear heat, ...

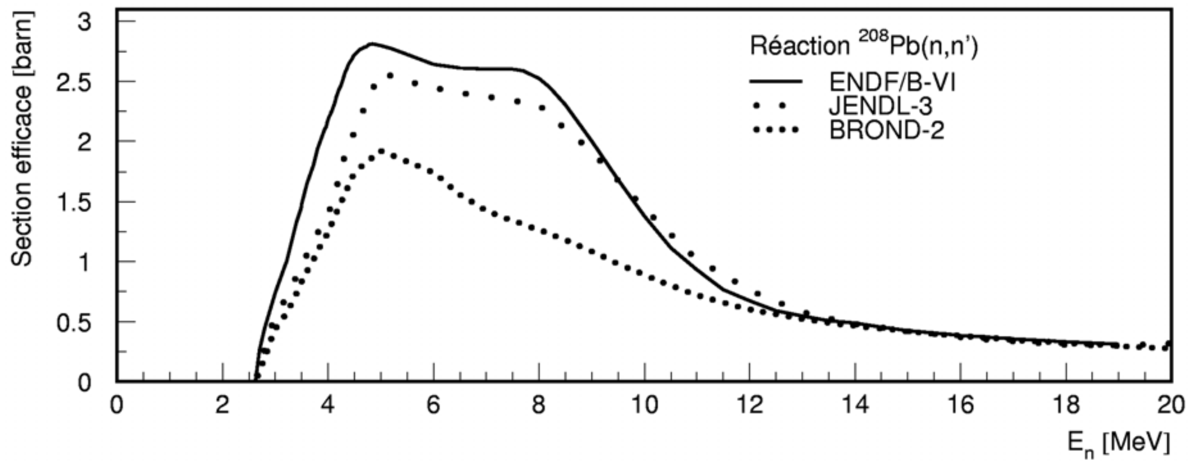
c) competition with (n,fiss), neutron multiplication, ...

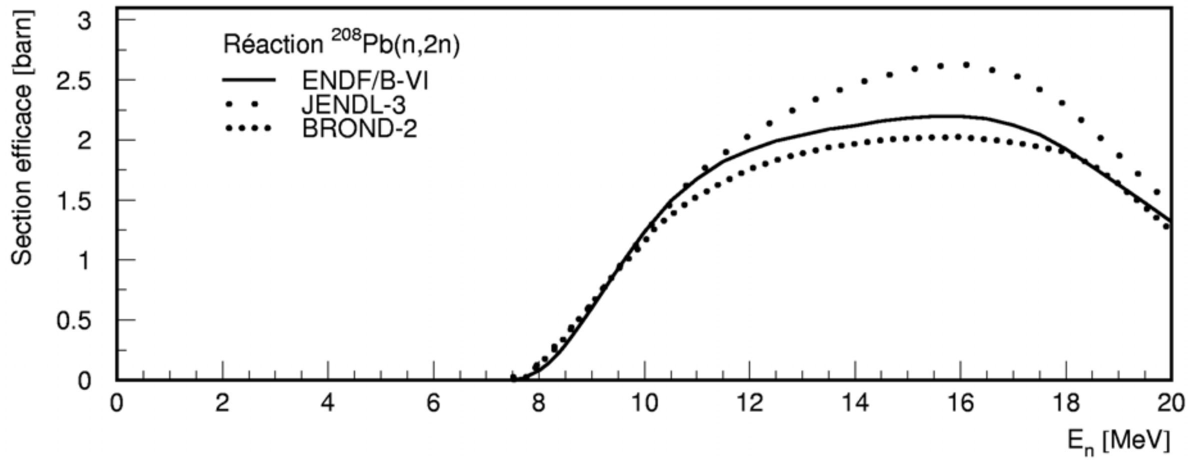
d) optical models, level density, pre-equilibrium treatment, γ-strength functions, ...

Motivation: physics with nTоF

(n,n') and (n,xn) reactions at energies from 0.1 to 35 MeV

^{208}Pb(n,n')

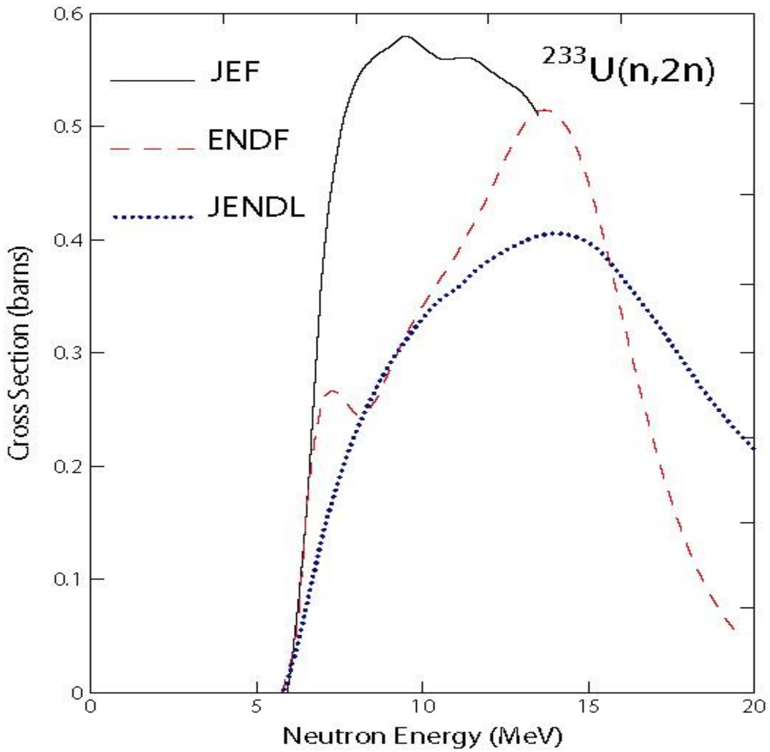


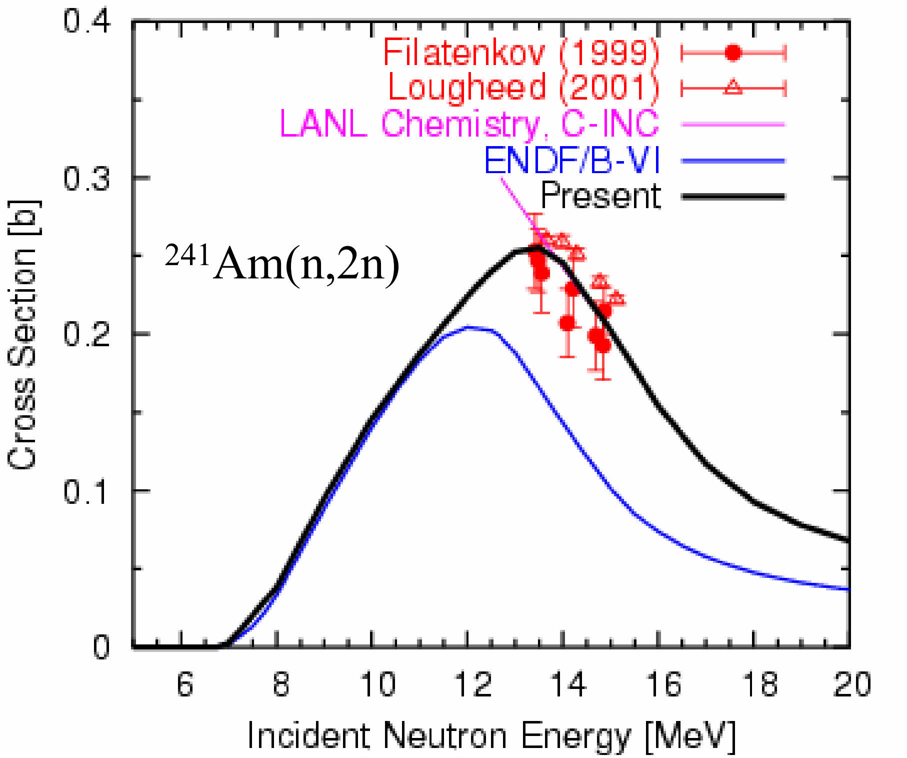


^{208}Pb(n,2n)

Motivation: physics with nToF

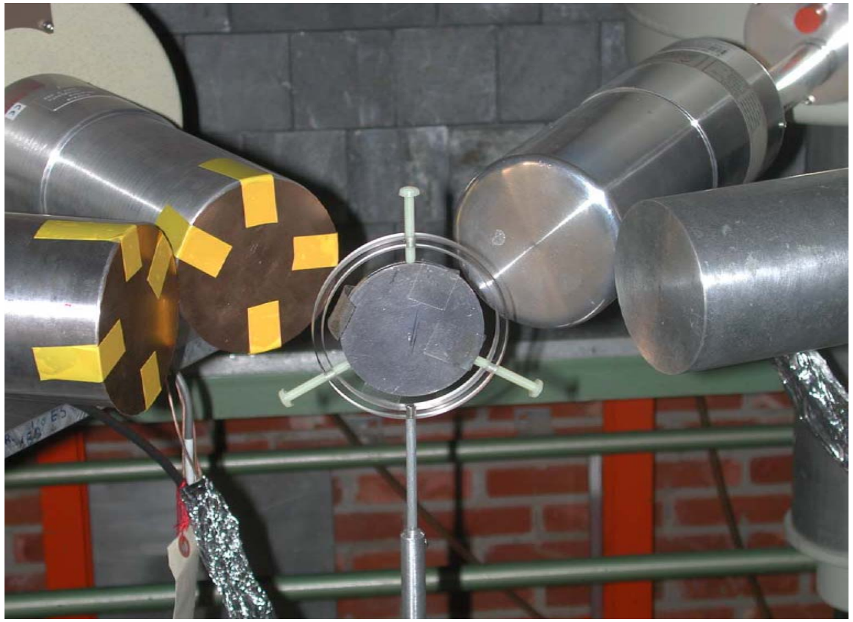
(n,n') and (n,xn) reactions at energies from 0.1 to 35 MeV

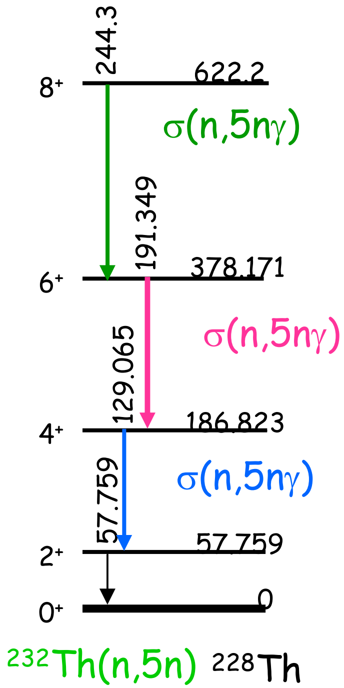




Example on (n,n') and (n,xn) reactions

- Detection of photons of excited states from (n,xn) reactions
- Pulsed neutrons beam
- HPGe detectors



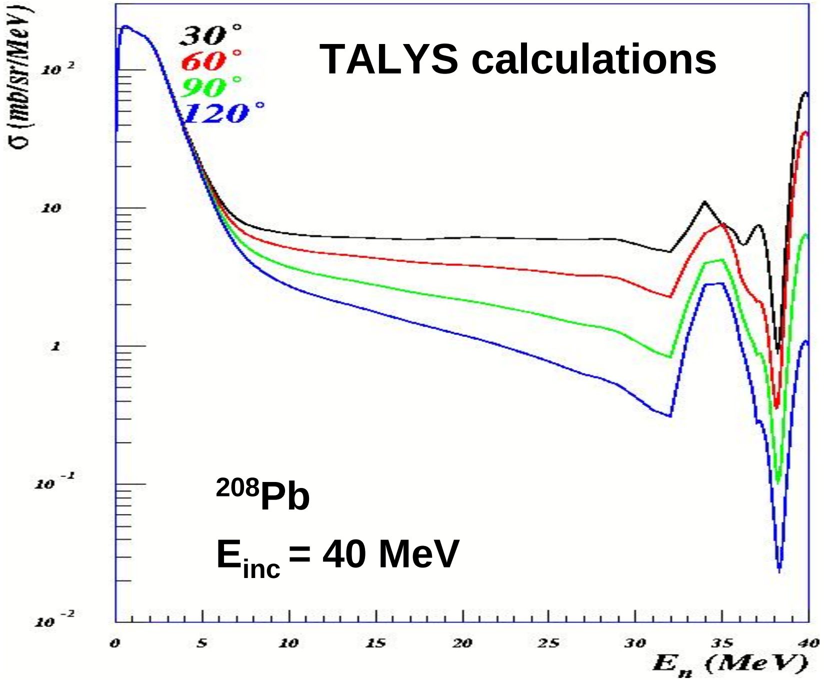


^{232}Th(n,5nγ) measured at Louvain-la-Neuve between 29 and 42 MeV

@NFS : - no gamma flash as at GELINA; 300 times more neutron flux
- ^{232}Th(n,3nγ) from 12 to 31 MeV (Th fuel cycle)
- (n,3n) and (n,4n) on Pb (ADS and fast reactors)

Example on (n,n') and (n,xn) reactions

- Important process for neutron energies E > 10 MeV
- Limited prediction power of models →



DD x-section measurements for (n,xn) reactions in coïncidence with neutron multiplicity

→ CARMEN @ NFS

Contact: ridikas@cea.fr, CEA Saclay

Why at SPIRAL2?

(n,n') and (n,xn) reactions at energies from 0.1 to 35 MeV

a) **If 20 m flight path → energy resolution better than 10 %**

b) **100 h run with 100 times smaller mass ←→ at Gelina in a 1000 h run!**

c) **Systematic studies on isotopic chains with samples of 0.5 g**

d) **No/little gamma flash, negligible attenuation corrections**

e) **Segmented Ge detectors → radioactive targets of even smaller samples!**

f) **Future experiments: Si, Fe/Ni, Zr/Mo, W, Pb, Th/U**

Motivation: physics with nToF

(n,fiss) reactions at energies from 0.1 to 35 MeV

a) **ADS, GenIV reactors, nuclear waste transmutation**

b) **Np, Am & Cm being major nuclei of interest; also U/Th fuel cycle chain**

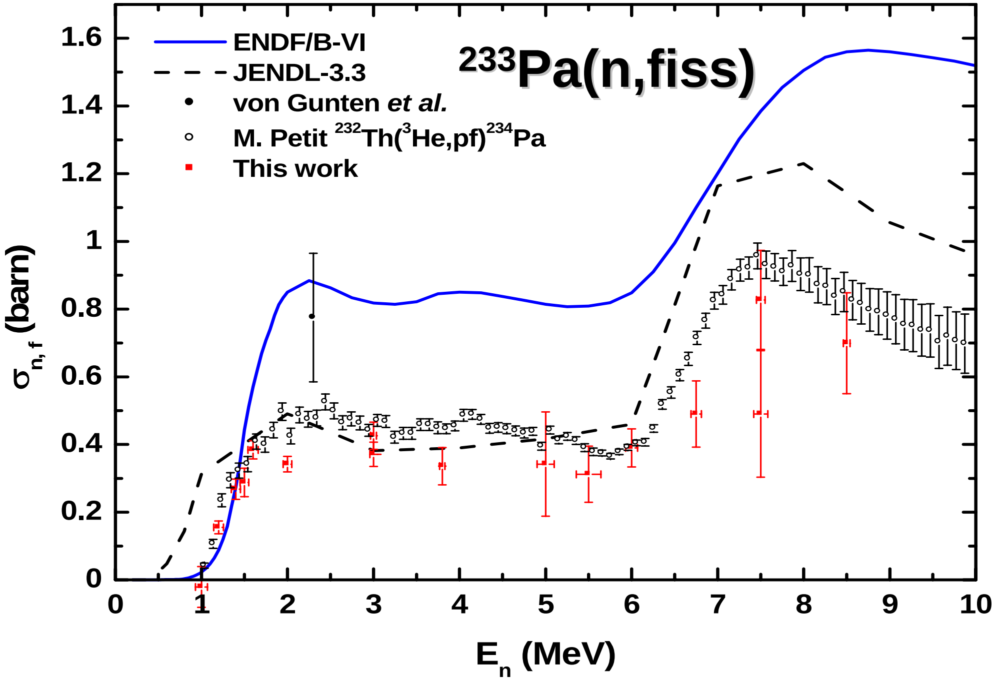
c) **Competition with (n,xn), charged particle emission, evaporation, ...**

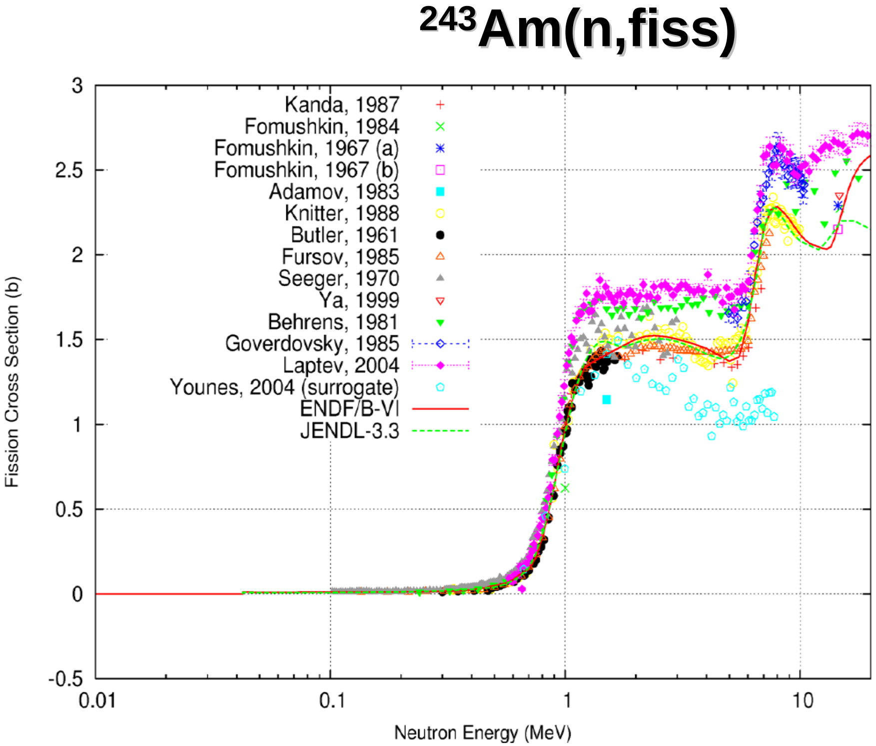
d) **Systematic of fission barriers, transition state level densities, ...**

e) **Systematic of fission fragment distributions in the wide excitation energy range**

Motivation: physics with nToF

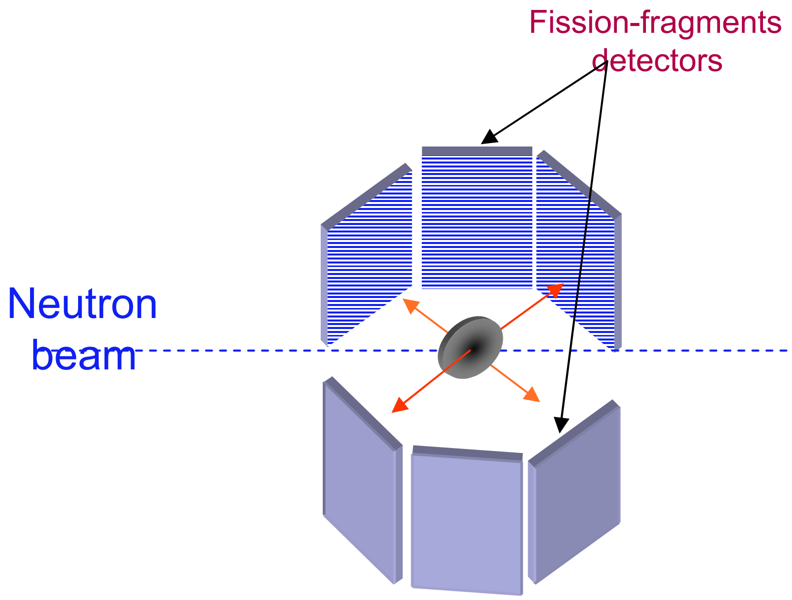
(n,fiss) x-sections at energies from 0.1 to 35 MeV

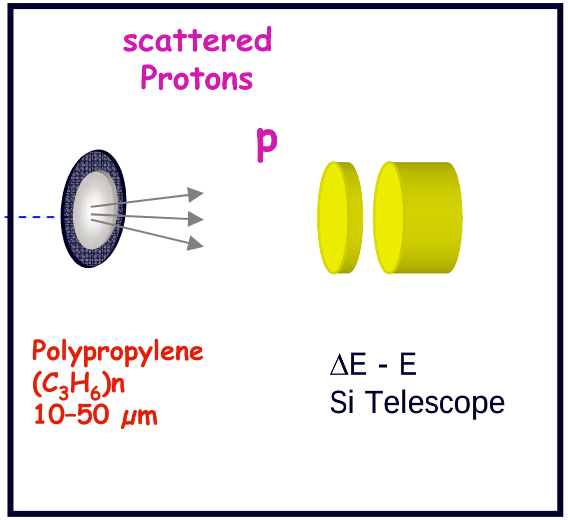




Contact: ridikas@cea.fr, CEA Saclay

Example of (n,fission) on ^{237}Np and ^{241,243}Am





Flux monitoring

E_n(MeV)	Fission rate(s^{-1}) NFS at 5m	Fission rate(s^{-1}) n-TOF@CERN at 20m
1	0.18	-
5	0.37	$8.24\ 10^{-3}$
10	1.42	$4.74\ 10^{-3}$
20	1.36	$2.33\ 10^{-3}$

@NFS :
- extremely intensive neutron flux
- small samples of actinides required
- systematic measurements from threshold to 35 MeV

Why at SPIRAL2?

A.2 → (n,fiss) reactions at energies from 0.1 to 35 MeV

a) With 5 m flight path energy resolution better than 10 %

b) 100 h run would give 3 % statistics in 0.1 MeV energy bins

c) Systematic studies on isotopic chains with samples of <1 mg !

d) Future experiments:

^{230,232}Th, ^{231}Pa, ^{233,234,235,236,238}U, ^{236,237}Np, ^{239,240,241,242,244}Pu, ^{243}Am, ^{245,246,247,248}Cm

and β-emitters ^{233}Pa and ^{241}Pu

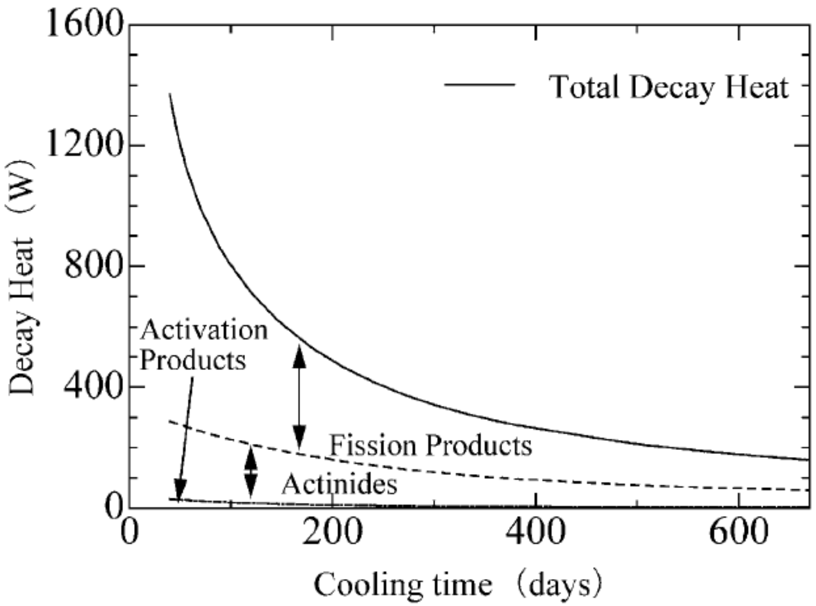
→Full excitation curve at the same installation!

Motivation: physics with nToF

Studies of fission fragments

Major fission products studied:
Rb, Sr, Y, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm and Eu

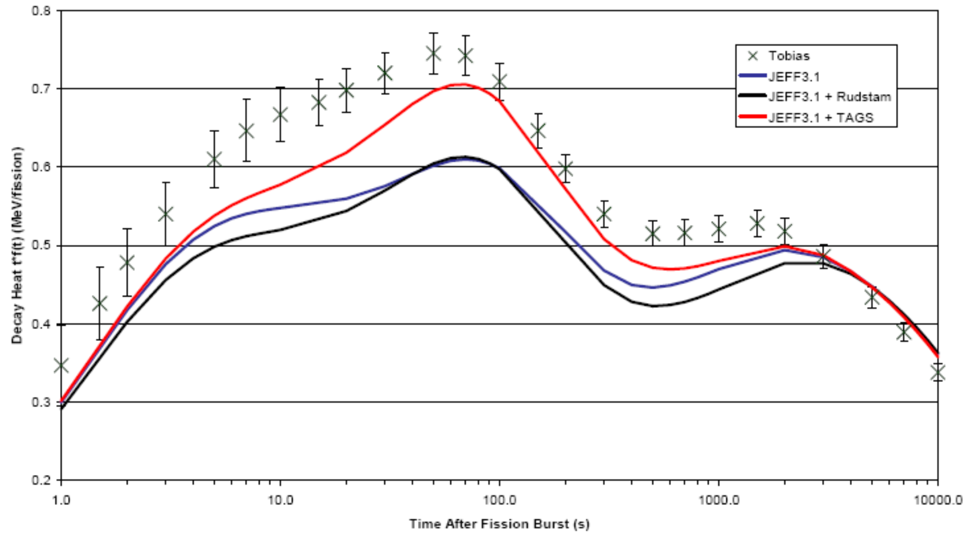
Repartition of decay heat of spent MOX fuel



Decay type: α - 1 %, β - 52 %, γ - 47 %

Influence of new measurements:

- mean energies of decay γ
- half-lives and branching ratios



Fundamental data needs:

a) fission yields of different actinides

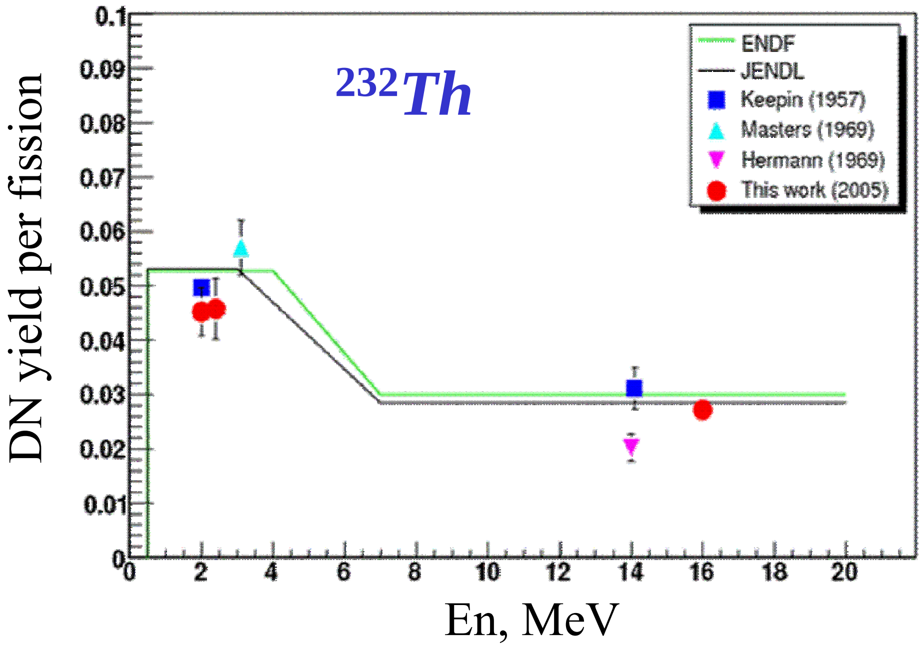
b) decay data (half-lives, branching ratios, energy spectra of decay particles, etc.) of fission products

Delayed neutron yields and time spectra for MAs

Strong decrease of DN yields with actinide mass!

^{A}Z	$\beta = \upsilon_d/\upsilon_{tot}$
^{232}Th	0.0203
^{233}U	0.0026
^{235}U	0.0064
^{238}U	0.0148
^{239}Pu	0.0020
^{241}Pu	0.0054
^{241}Am	0.0013
^{243}Am	0.0024
^{242}Cm	0.0004

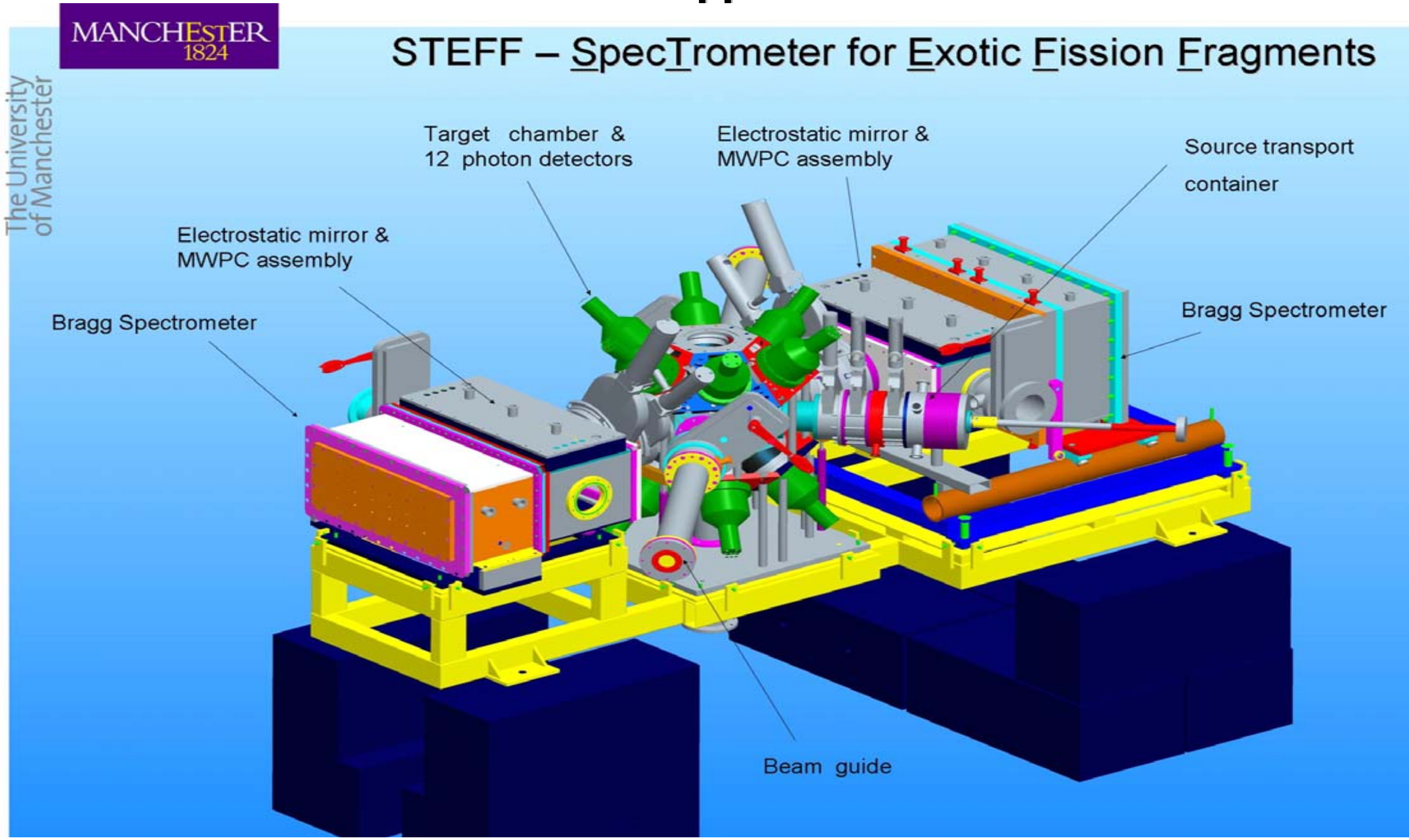
β_{eff} : **PWR** versus **Fast Reactor with MAs**
~600pcm ←→ ~200-300pcm
Constraints on the reactor control!



Fundamental data needs:

a) fission yields of Minor Actinides Y(A,Z)
b) decay data (half-lives, branching ratios, etc.) of fission products

Goal: permanent installation of STEFF@NFS both for fundamental & application oriented research



- Prompt gamma-ray spectroscopy of exotic n-rich nuclei
- Delayed gamma-ray spectroscopy (nanosecond isomeric states)
- Isotopic & mass yields
- Gamma-ray multiplicity
- Prompt neutron multiplicity

} From low-energy fission and as a function of excitation energy !

Motivation: activation-irradiation

Two irradiation stations can be installed in the converter cave :

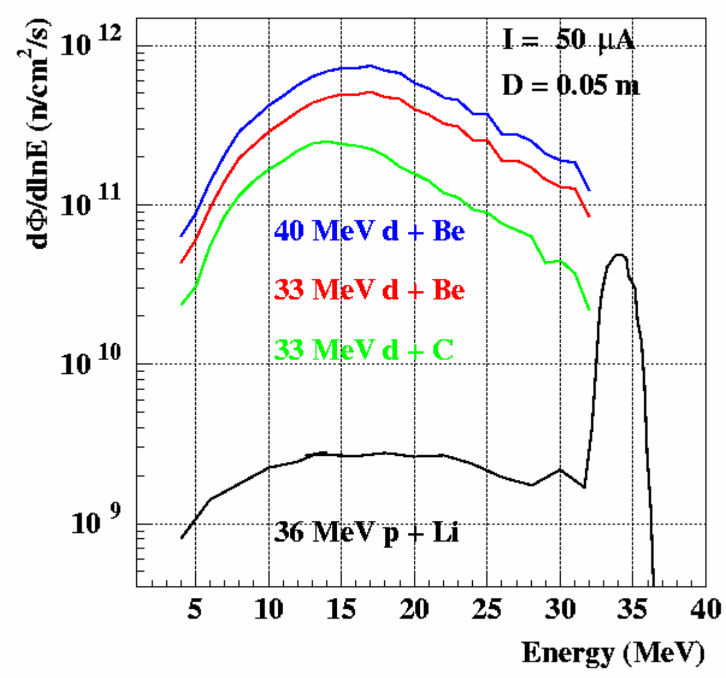
- Neutron induced reactions

  The sample is put very close of the converter

  White source <E> = 14 MeV

  $\Phi > 5.10^{11}$ n/s/cm^2 for $I_d = 50\ \mu A$

  Quasi-monoenergetic (Li converter on carbon back-up)



- Proton and Deuteron induced reactions

→ Cross-section measurement :

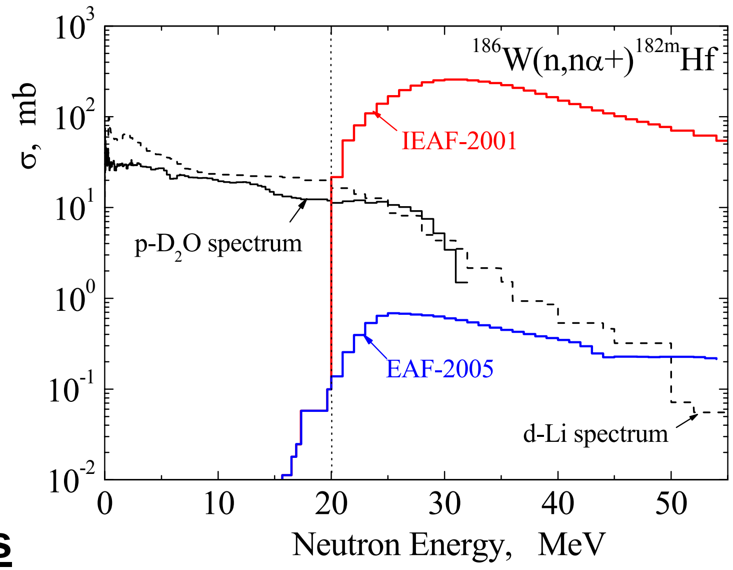
- Counting room for off-line activity measurement
- Detectors for flux monitoring

I_{max} limited to 50 μA

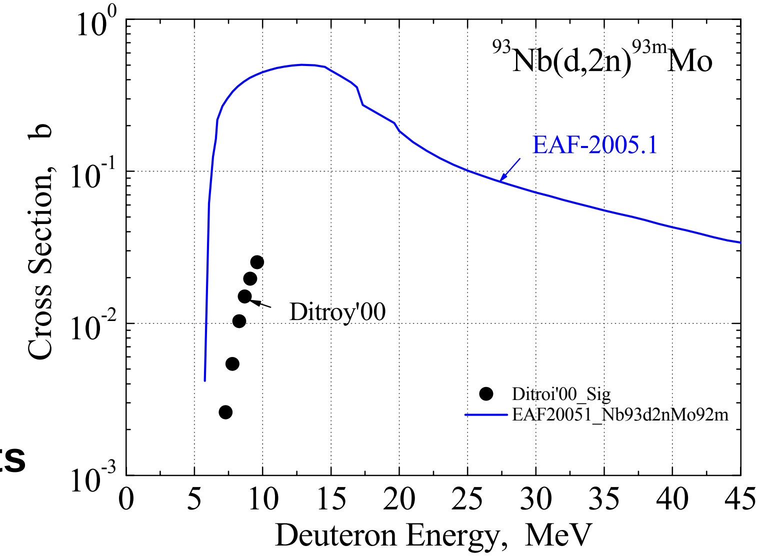
- Low power deposition on converter < 2 kW
- Reduced activation → « easy » sample manipulation

Motivation: activation-irradiation

IFMIF : material testing for fusion technology
neutrons produced by 40 MeV d + Li



<u>Neutron, proton and deuteron induced reactions</u>



Data scarce or not existing

Large discrepancies between data base

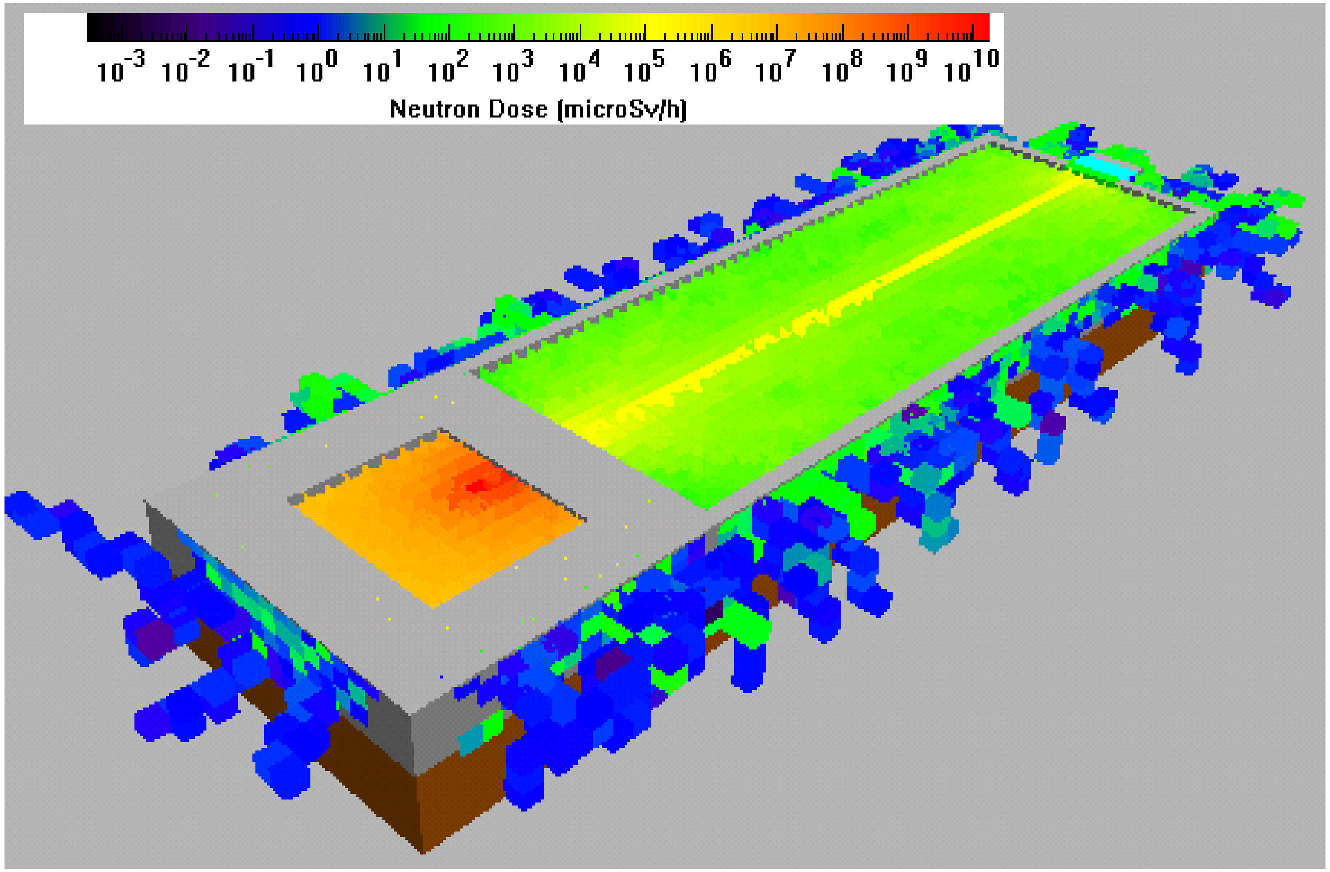
Material to be studied for IFMIF :

Al, Fe, Cr, Cu, Nb cavities & beam transport elements

Be, C, O, N, Na, K, S, Ca, Fe, Cr, Ni Li loop

Last progress at NFS…

1) Doses calculated for 100 μA d + Be (1 cm)



2) List of actinide targets provided
3) Activation of the targets, beam dump and air has been performed
4) Tritium production rates were estimated

Summary

Neutron beam facility

White and quasi-monoenergetic spectra

Very high flux in the 1-40 MeV range and good energy resolution

Complementary to the existing n-ToF facilities

Both fission & fusion related research

Irradiation facility

Neutrons: white and quasi-monoenergetic spectra

Protons & deuterons

Cross-section measurement by activation technique

Test bench for IFMIF

high power accelerator (40 MeV deuterons)

similar target materials

similar neutron energy spectra

similar challenges

NFS is “well advanced” compared to RIB production station

Maximum Intensity limited to 50 μA (2kW) → « simple converter design »

Could start as soon as the LINAG is ready → ~2012

Neutrons For Science (NFS) at SPIRAL-2

X. Ledoux[1)], M. Aïche[2)], G. Ban[3)], G. Barreau[2)], P. Baumann[4)], P. Bem[5)], E. Berthoumieux[6], V. Blideanu[6)], J. Blomgren[7)], S. Czajkowski[2)], P. Dessagne[4)], D. Doré [6)], E. Dupont[6)], T. Ethvignot[1)], U. Fischer[8)], F. Gunsing[6)], B. Jacquot[9)], B. Jurado[2)] , M. Kerveno[4)], F. R. Lecolley[3)], J. L. Lecouey[4)], F. Negoita[10)], S. Oberstedt[11)], M. Petrascu[10)], A.J.M. Plompen[11)], F. Rejmund[9)], D. Ridikas[6)], G. Rudolf [4)], O. Shcherbakov[12)], G. Smith[13)], S.P. Simakov [8)] , J. Taïeb[1)], I. Tsekhanovich[13)]

1) CEA/DIF, DAM/DPTA, 91980 Bruyères-le-Châtel Cedex, France

2) CEN Bordeaux-Gradignan, 33175 Gradignan, France

3) LPC, ISMRa et Université de Caen, CNRS/IN2P3,France

4) IPHC, Strasbourg, France

5) Nuclear Physics Institute, 25068 Řež, Czech Republic

6) CEA Saclay, DSM/IRFU, Gif-sur-Yvette, France

7) Department of Neutron Research, Uppsala University, Uppsala, Sweden

8) FZK, Karlsruhe, Germany

9) GANIL, CEA/CNRS, Caen, France

10) NIPNE, Bucharest, Romania

11) IRMM, Geel, Belgium

12) PNPI, Gatchina, Russia

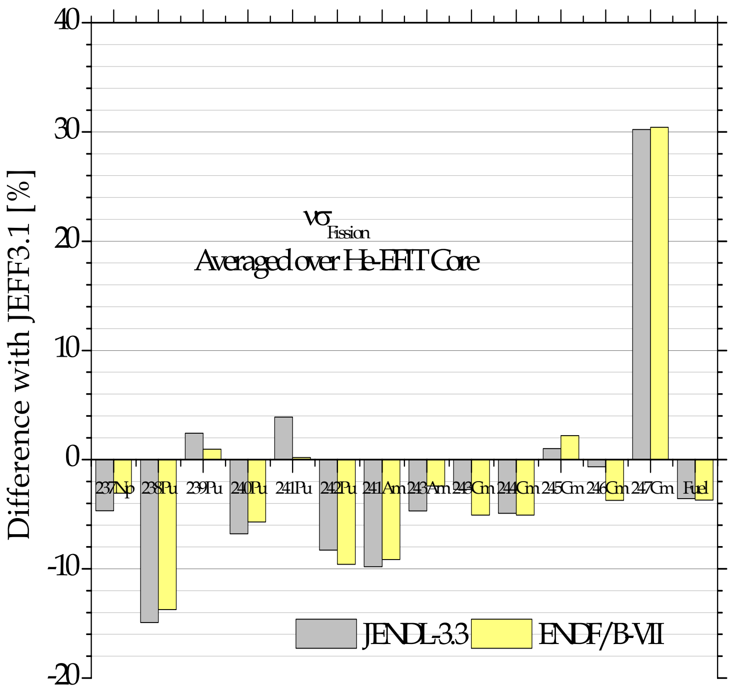
13) University of Manchester, Manchester, UK

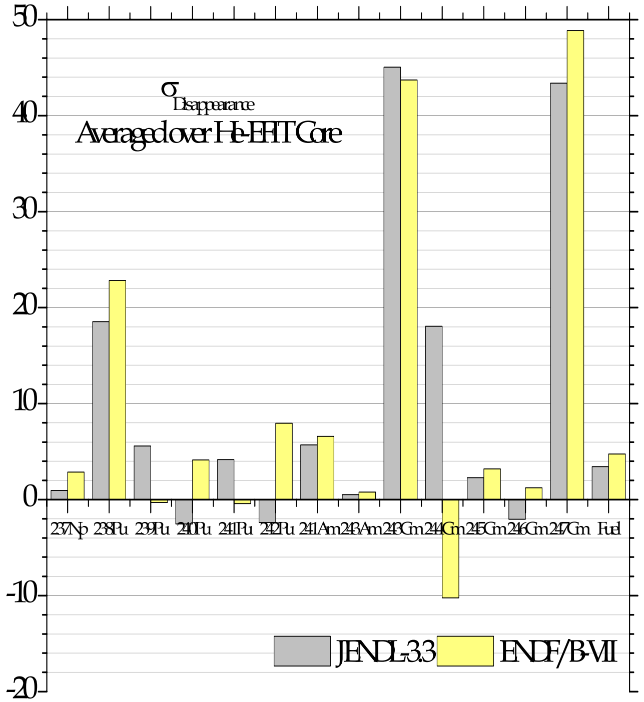
…

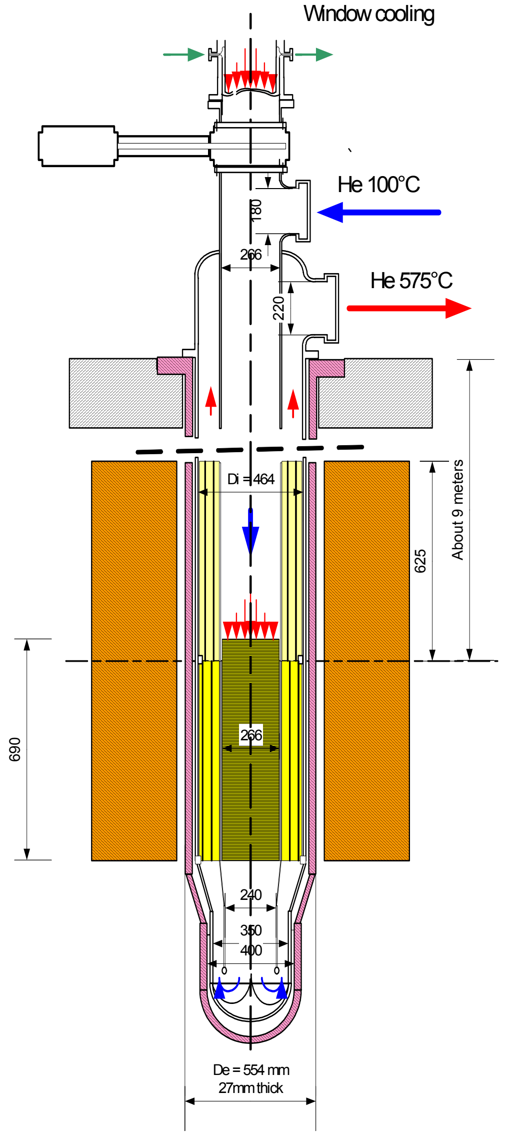
ADS example: He-EFIT core calculations

Sensitivity to nuclear data: Pu+MA

Library	He-EFIT core Keff	Neutron multiplication
JEFF3.1 (Reference)	0.97606±0.00179	42
JENDL-3.3	0.94952±0.00137	20
ENDF/B-VII	0.95615±0.00154	23

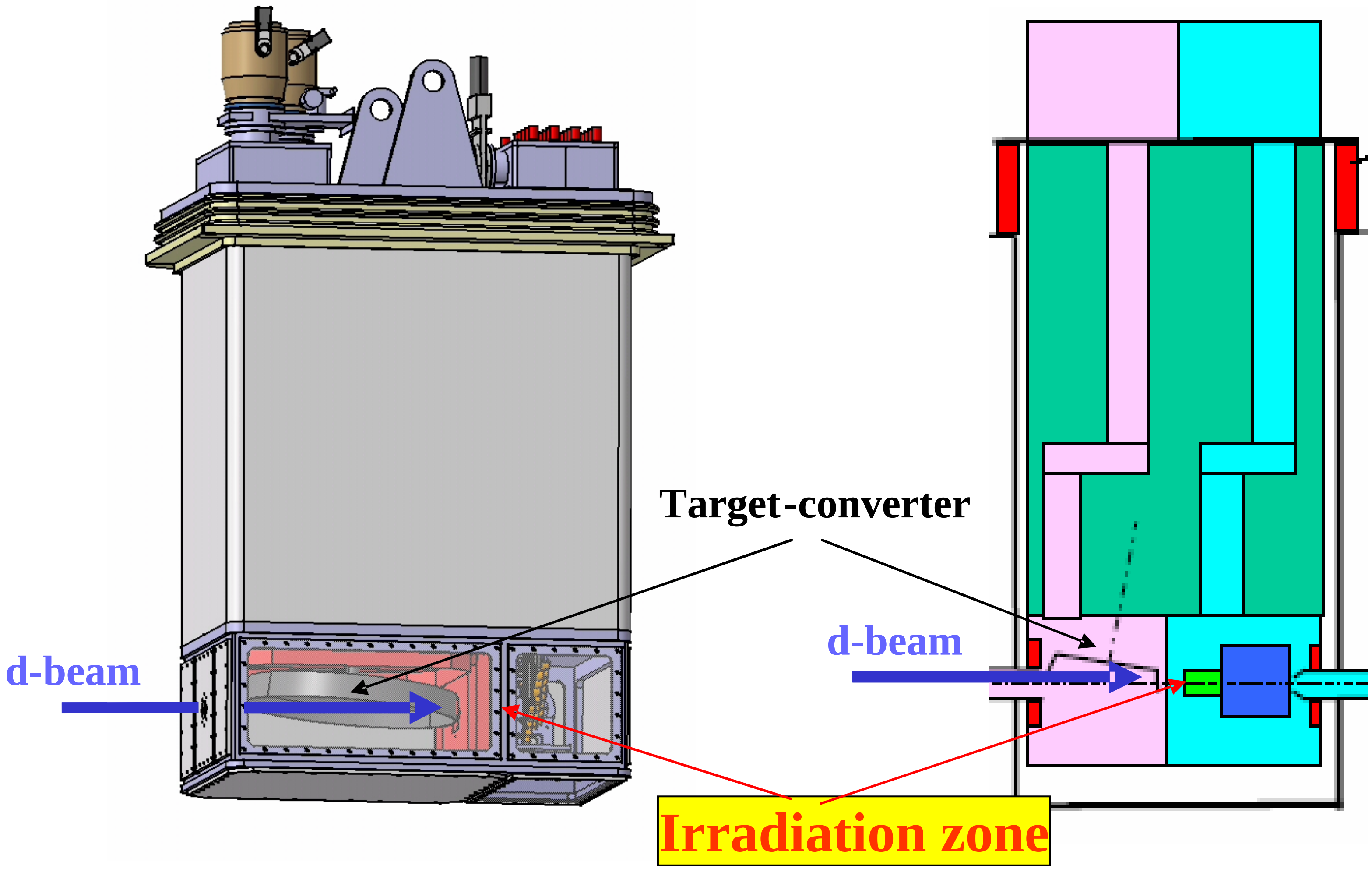




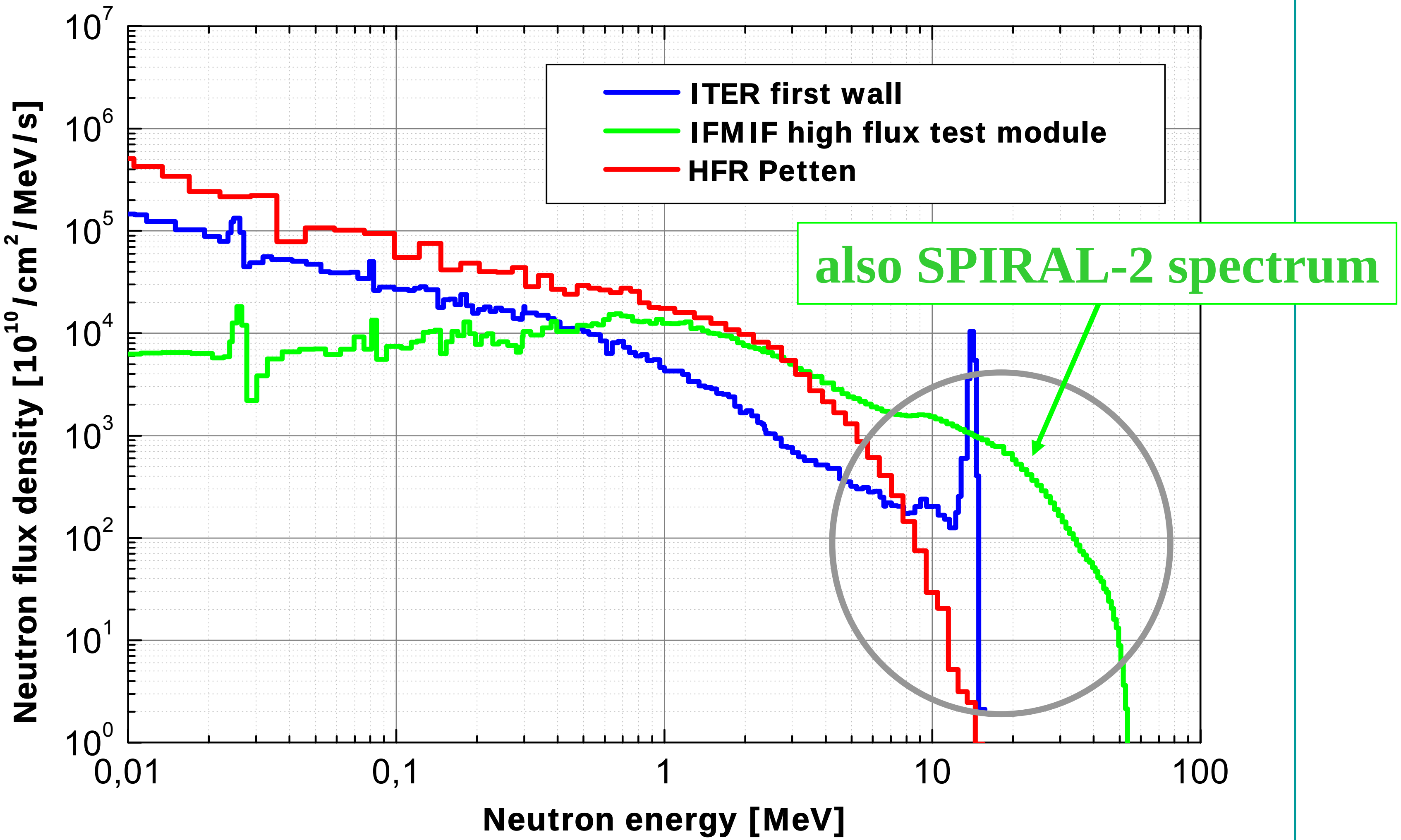


Plug system at SPIRAL-2 (if full power is used)

Proposal B: material irradiations for fusion applications (e.g., ITER)

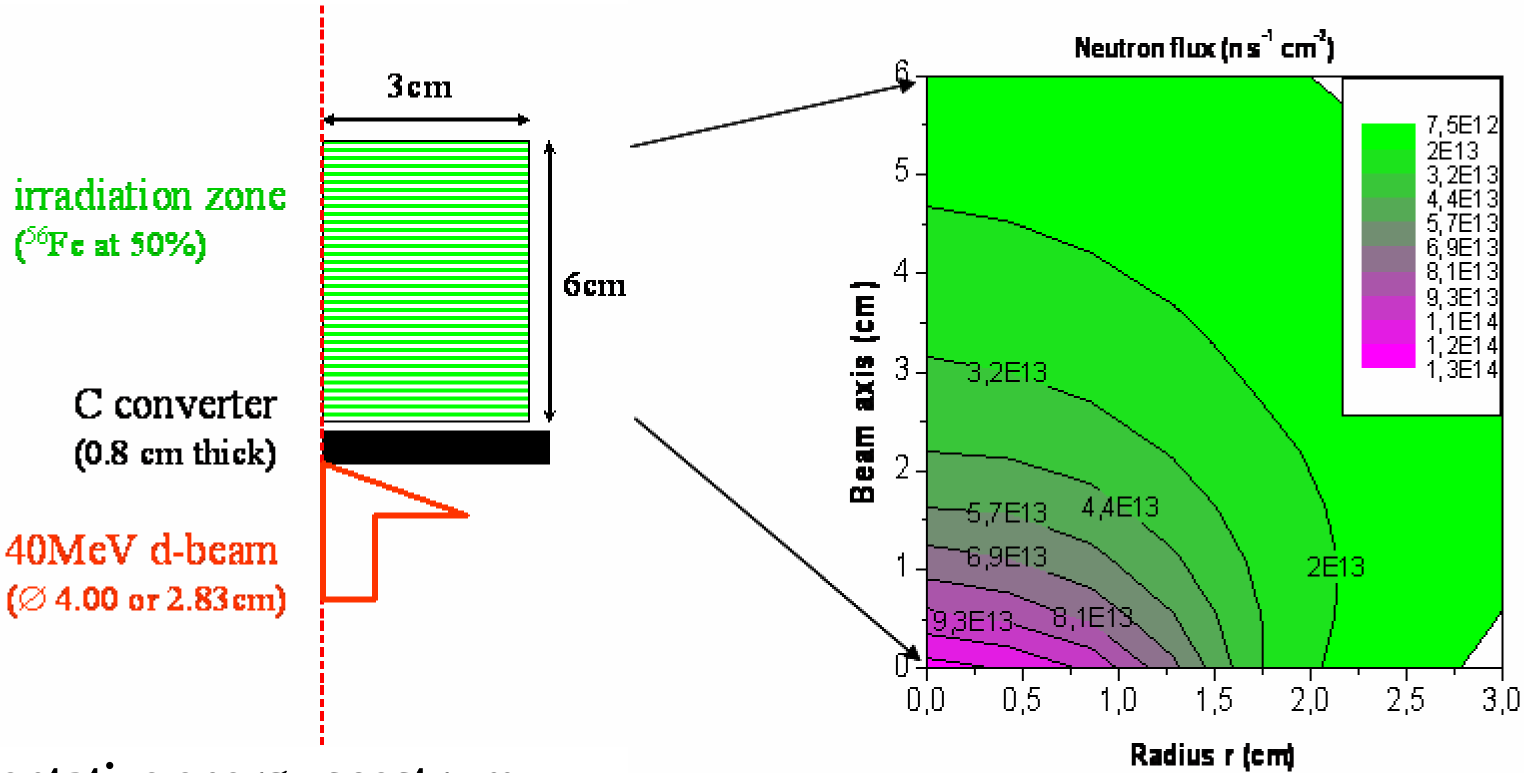


Neutron flux spectra: IFMIF/fusion/fission



U. Fischer, Fast Neutron Physics Workshop, Dresden, 5-7 September, 2002

Neutron flux characteristics at SPIRAL-2



- Representative energy spectrum
- Neutron flux: > 5x10^{13} n/(s cm^2)
- Damage rates: > 3dpa/fpy
- Useful volume: ~10 cm^3
- Variable temperature: 500-1000°C

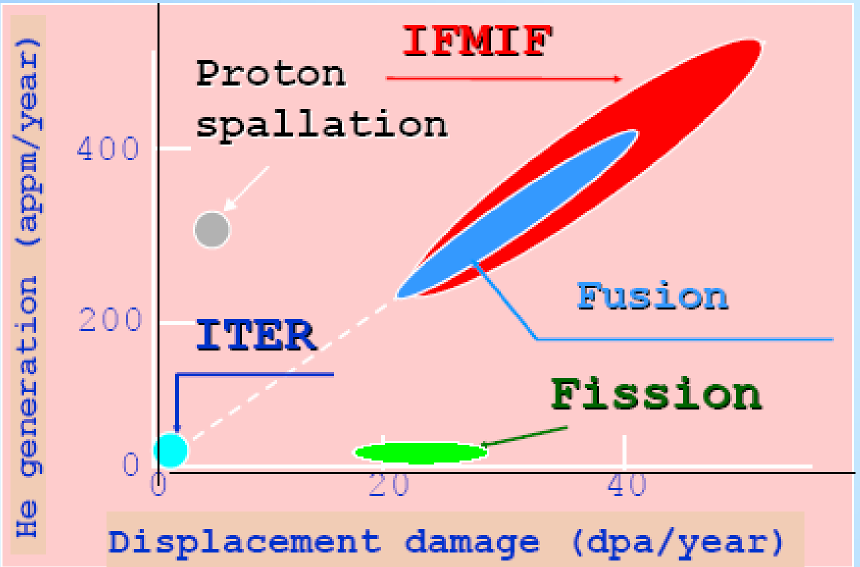
interest

- CEA Cadarache, DSM/DRFC
- CEA Saclay, DEN/DMN/SRMA
- IFMIF collaboration, EURATOM

Motivation: activation-irradiation

B.1 → fusion related research

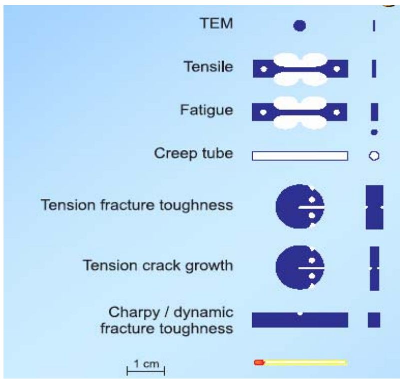
Maximal values	Neutron flux ($n\ s^{-1}\ cm^{-2}$)	Damage rate (dpa/fpy)	He - prod. (appm/fpy)	H - prod. (appm/fpy)	Nuclear heat (W/cm^3)
SPIRAL-2	**1.1×10^{14}**	**7**	**95**	**378**	**3**
ITER-?	**4.0×10^{14}**	**12**	**140**	**540**	**12**



dpa: displacement per atom
appm: atomic parts per million

SPIRAL-2 →

1. similar irradiation conditions as ITER
2. variable temperatures available
3. irradiations of miniaturized samples
4. qualification of dedicated modeling tools
5. test bench for IFMIF

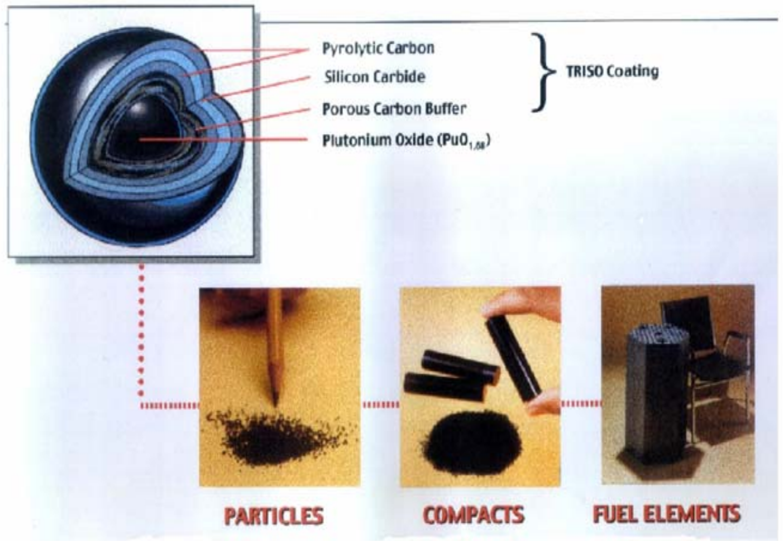


Motivation: activation-irradiation

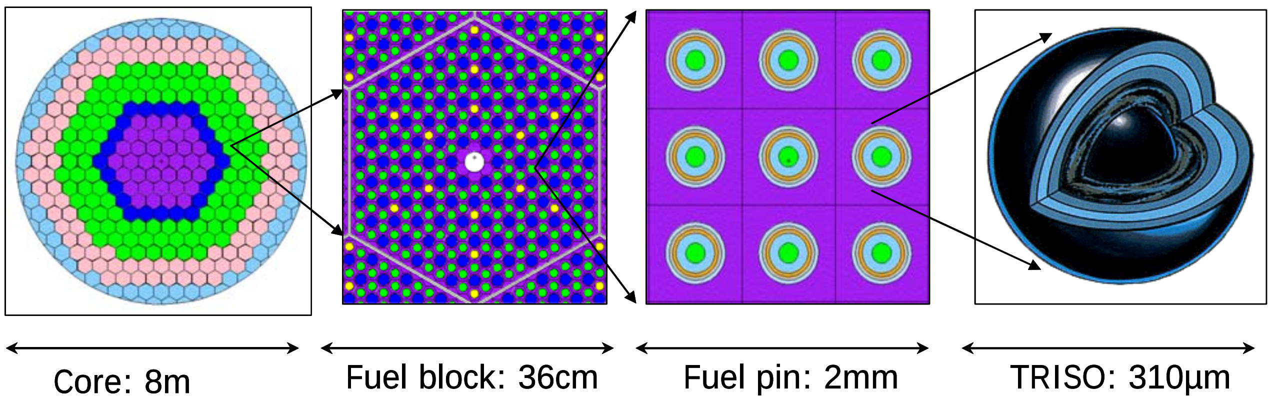
B.3 → fission related research

attractive features of GT-MHR

- high conversion efficiency ~45%
- coated TRISO fuel
- high burn-up rates ~90% for ^{239}Pu
- He cooled, high temperature

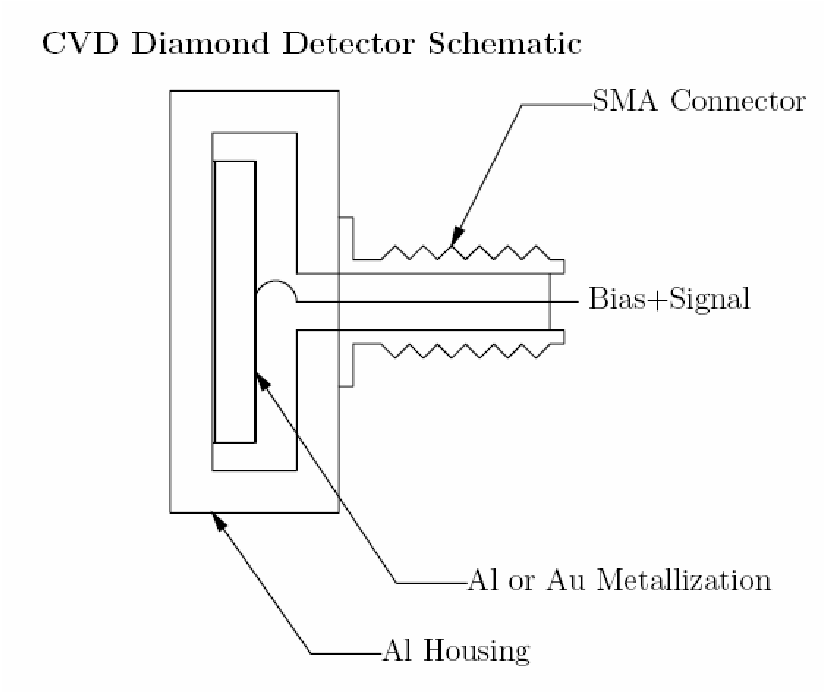


3D geometry including micro-particles with MC

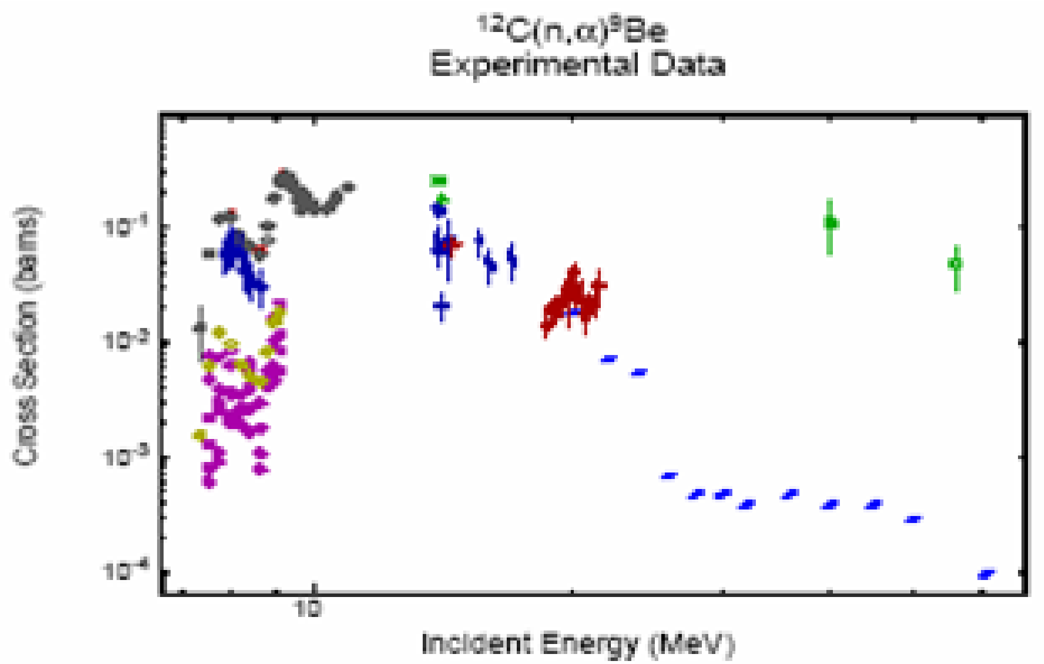


Motivation: activation-irradiation

detector testing



1. Calibration is urgently needed
2. Knowledge of (n,chp) reactions is poor
3. Desired fluence in 1 hour!



Motivation: activation-irradiation

Astrophysics applications

Preparation of radioactive samples

- Use of (n,p), (n,alpha), (n,2n) reactions
- irradiation for a few weeks → 10^{17} atoms created
- e.g., production of ^{85}Kr via ^{85}Rb(n,p) or ^{88}Sr(n,alpha)

Material damage: gas production

Production of H, D, T, ^{3}He, ^{4}He with high energy neutrons:

C, Si, Al, Fe, Ni, Zr, W as targets

Contact: ridikas@cea.fr, CEA Saclay